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Conservation Tillage Mitigates Soil Organic Carbon Losses While Maintaining Maize Yield Stability Under Future Climate Change Scenarios in Northeast China: A Simulation of the Agricultural Production Systems Simulator Model

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Abstract: Global warming may reduce maize yields and soil organic carbon (SOC), potentially threatening global food security and soil health. To address this concern in Northeast China, one of the world's major maize production areas, the maize Agricultural Production Systems Simulator Model (APSIM) was used to evaluate how different tillage methods and straw return practices affect maize yields and SOC under future climate scenarios. The purpose of this study is to deal with the threat of global warming to the yield and SOC in the northeastern maize-producing areas, explore sustainable agricultural management strategies to stabilize the yield, enhance the soil carbon pool, counter the impact of climate change, and seek ways to ensure regional food and soil health. This study explored three tillage methods—plowing tillage (PT), rotary tillage (RT), and no-tillage (NT)—and two straw return methods—straw return (SR) and no straw return (SN)—under two Representative Concentration Pathway (RCP) scenarios: RCP4.5 and RCP8.5. The results showed that under the climate change scenarios: (1) For different tillage methods, no-tillage (NT) management showed the greatest increase in crop yield at 6.2%. SOC is highest under NT in the 0–20 cm soil layer under both straw return methods and climate scenarios. (2) For different straw return methods, SOC decreases when the straw is removed (SN) but increases when the straw is returned (SR) in both scenarios. Soil organic carbon density (SOCD) declines but can be mitigated by straw return. (3) Overall, tillage and straw return practices can significantly impact SOC under RCP4.5 but not under RCP8.5. Tillage and straw return practices together explain more than 50% yield changes under climate change scenarios. Through the modeling approach, this study revealed the potential benefits of integrating tillage and straw management practices to sustain maize yields and SOC. These practices can mitigate long-term climate change impacts on crop yields and soil health.

Keywords: APSIM-maize; crop model; climate change; conservation agriculture; soil health

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1. Introduction

With global temperatures projected to rise by 2.6–4.8 °C by 2100, crop production could be severely impacted, threatening the productivity of staple crops and jeopardizing global food security [1,2]. Extreme weather events always disrupt physiological processes in crops, resulting in significant yield reductions [3,4]. At the same time, however, rapid population growth has significantly increased the demand for crops like maize [5], potentially leading to social and economic challenges if yields are affected and fail to meet demand. Maize (*Zea mays* L.) is a crucial food and forage source, essential for global food security. It has the largest sown area and the highest production among grain crops in China [6]. The Northeast region of China, known as the "Golden Corn Belt", accounts for 30% of the country's maize production (National Bureau of Statistics of China, 2001–2019). It is vital for ensuring abundant maize production and enhancing China's grain resilience to external risks [7,8]. It is crucial to study maize's adaptability and yield performance under future climate change scenarios and different management strategies.

As a vital carbon pool in terrestrial ecosystems, SOC plays a key role in mitigating climate change, improving soil quality, and maintaining fertility [9]. Incorporating an appropriate amount of straw into the soil increases SOC and enhances soil carbon sequestration [10]. Additionally, returning straw to the field helps improve soil nutrient availability, reduce environmental pollution, and promote sustainable agricultural development [11,12]. Thus, returning straw to cropland is regarded as the primary method for efficient and sustainable use of straw resources [13]. Soil tillage is also a significant influence on SOC. As the traditional tillage methods, plowing tillage (PT) and rotary tillage (RT) eliminate weeds, reduce pests and diseases effectively, improve soil structure, increase permeability, promote root growth, and distribute soil fertility evenly [14–16]. However, RT and PT accelerate soil organic matter decomposition, making nutrient preservation challenging. This results in a long-term decline in soil fertility, harming the conservation of black soil in northeast China [17–19]. Although no-tillage (NT), as a conservation tillage method, may have the possibility to increase weeds, pests, and soil compaction over time [20,21], it boosts surface soil organic matter, enhances fertility, reduces moisture loss, lowers production costs [22,23], and increases maize yields [24]. In the context of global efforts to combat climate change, countries worldwide are striving to optimize agricultural practices for enhanced carbon sequestration. China, with its vast agricultural acreage and diverse agro-ecological zones, serves as a living laboratory for innovative tillage and straw management strategies. As one of the largest regions for agricultural development in China, the findings from northeast China have the potential to catalyze a paradigm shift in sustainable agricultural approaches globally.

There are always trade-offs in choosing proper tillage and straw return methods to improve the overall performance of maize production and sustainability. Previous studies have conducted field experiments to investigate the combination of conservation management to maize production and soil fertility to increase carbon inputs and reduce carbon losses to maintain and increase SOC [25,26]. However, the field experiments have limited insights into crop performance under climate change conditions regarding predictivity. The crop model simulation can provide predictions on the maize performance under climate change and different management, for example, a previous study found that no-tillage, straw return, and manure application enhance SOM in arid cropland in northwest China [27]. So, the simulation approach of crop models would be a promising means to address this kind of research question.

With the hypothesis that conservation practices could improve soil quality while increasing crop productivity in a main maize production region from a long-term perspective [28], we explored the effects of different tillage practices and straw return on maize yield and SOC under two future climate scenarios based on the Agricultural Production Systems Simulator Model (APSIM). The objectives of this study are to (1) investigate the effect of climate change on the yield performance under different combinations of three tillage practices (PT, RT, and NT) and straw-returning methods (no-straw return SN and straw return SR); (2) investigate the effect of climate change on the SOC and SOCD under different combinations of three tillage practices (PT, RT, and NT) and straw-returning methods (SN and SR); (3) systematically reveal the contribution of different tillage practices and straw-returning methods on the soil carbon contents and maize yield under climate change scenarios. In this study, APSIM was used to accurately simulate solutions the problem that previous studies mostly relying on field trials and crop performance found difficult to measure under climate change. We hope this study can provide theoretical guidance for the development of climate-smart agriculture in Northeast China and for choosing the proper conservation management combinations.

2. Materials and Methods

2.1. Study Area

This study was conducted at the Institute of Crop Science, Chinese Academy of Agricultural Sciences, Gongzhuling City, Jilin Province (Figure 1), which is located in the central part of Jilin Province (43°30′23″ N, 124°48′34″ E, 220 m above sea level), one of the major dry high-yielding maize-growing areas in northeast China. Gongzhuling City has a temperate continental monsoon climate with significant seasonal temperature, rainfall, and light changes. Spring (March to May) is dry and windy with rapid warming; summer (June to August) is hot and rainy; autumn (September to November) is warm with sunny weather; and winter (December to February) is long and cold. The average annual temperature is 5.6 °C, the annual precipitation is 562 mm, which is concentrated in May–September, the frost-free period is 144 days, and the sunshine hours are 2710 h. The pre-experimental soil properties were as follows: pH: 7.6, SOC: 12.7 g·kg^{-1}, total nitrogen (TN): 1.4 g·kg^{-1}, total phosphorus (TP): 0.61 g·kg^{-1}, total potassium (TK): 18.4 g·kg^{-1}, available nitrogen (AN): 114.0 mg·kg^{-1}, available phosphorus (AP): 11.8 mg·kg^{-1}, available potassium (AK): 158.3 mg·kg^{-1} [29–31].

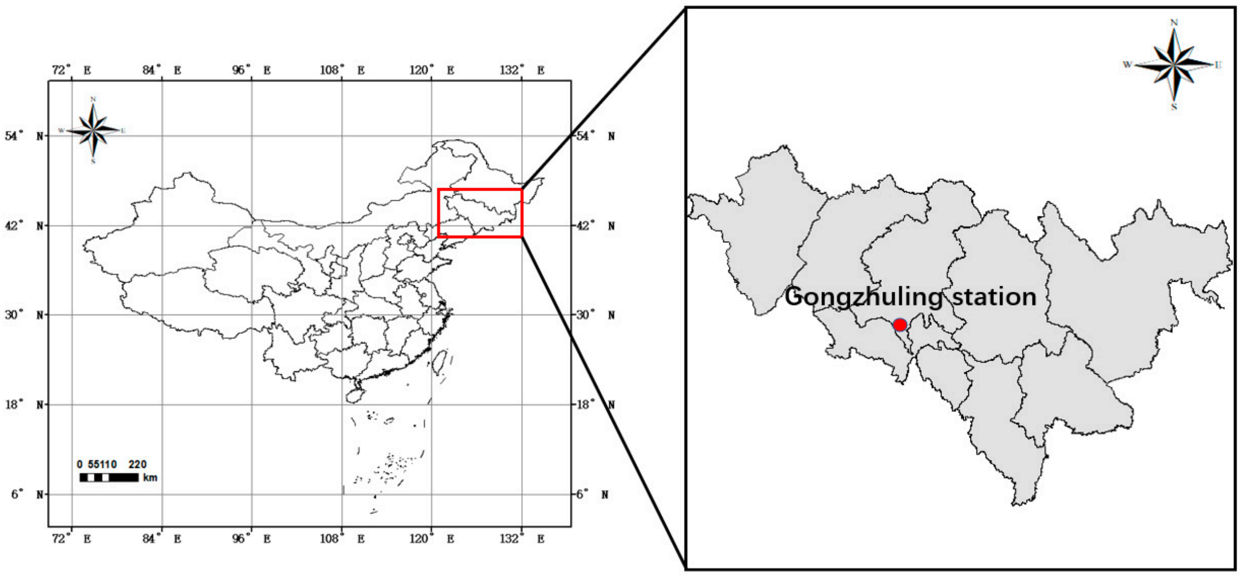

Figure 1. The Gongzhuling experimental station of the Chinese Academy of Agricultural Sciences.

2.2. Data Source

The climate data required for the experiment include daily radiation, maximum temperature, minimum temperature, rainfall, evapotranspiration, sunshine duration, and 2 m wind speed. The meteorological data part of the historical meteorological data (1980–2010) was obtained from the Climate Data Sharing Service of China Meteorological Administration (http://data.cma.cn/, accessed on 1 January 2019), and for future climate prediction, we used the data in CMIP5 (Coupled Model Intercomparison Project Phase5) under RCP4.5 and RCP8.5 (Representative concentration pathways) climate scenarios using data (2011–2100) from the HadGEM2-ES (Horizontal resolution of atmospheric data: Lat. $1.88^{\circ} \times$ Lon. 1.25°) model [32–34]. Soil data were obtained from the China Soil Scientific Database, which is operated by the Institute of Soil Science, Chinese Academy of Sciences.

2.3. Experimental Design and Field Management

In this experiment, Xianyu-335 maize variety was used as the experimental material, and three different tillage methods of PT, RT, and NT were used, combined with two different field management measures of straw return and straw non-return, to investigate the dynamic changes in maize yield and SOC under future climate change. The experimental plots were designed in a completely randomized group trial, and each plot was 45 m $\times$ 8 m. Maize was planted on 1 May of each year with a sowing depth of 3–4 cm, a sowing row spacing of 60 cm, and a pre-plant application of basal fertilizer urea of 244.57 kg ha^{-1}. In addition, maize straw was returned to the field in a full amount of 1.2×10^4 kg·ha^{-1}, and no supplemental fertilizer was applied to maize in the later stages of growth. Insect and disease prevention were performed by regular spraying during the growing season of maize. Maize was harvested on 30 September each year and weighed for yield when moisture-dried back to 14%.

2.4. Model Descriptions

APSIM was developed by the Agricultural Production Systems Research Unit in Australia [35,36]. It is a process-based crop model that simulates daily crop development, growth, biomass production, and soil water and nitrogen dynamics as affected by the climate, cultivar selection, soil, and management practices. APSIM is a relatively extensive agricultural model, but its modular working principle can be adapted to different crops [37,38]. Maize is one of the crop modules which is widely used in the world and has been widely verified. APSIM has been calibrated and used in northeast China for simulating the growth and yield of maize. The previous results indicated that APSIM can be successfully used for simulating growth and yield for maize in Northeast China [39]. The model parameters were calibrated (years of 2009–2011) and validated (years of 2012–2013 and 2015) by applying field-measured maize yields before applying the model to Gongzhuling City in this study. In this study, the parameters of the APSIM maize module have been adjusted according to Table S1, including the parameters of thermal time during the reproductive period of maize. Furthermore, the input of soil profile properties includes the soil bulk density (BD), drained upper limit (DUL), 15 bar lower limit (LL15), total nitrogen (N), SOC, and pH values in different soil layers.

The coefficients of determination (R^2), D-index (D), root mean squared error (RMSE), and normalized root mean squared error (nRMSE) were applied to check the agreement between simulated values and observed. The values R^2 and D-index closer to 1 indicate that the simulation results are more accurate; the simulation was identified as excellent if nRMSE was less than 10%, good if nRMSE was between 10% and 20%, fair if nRMSE was between 20% and 30%, and poor if nRMSE was greater than 30% [40–42]. The model performance evaluation indicators were computed using the following Equations:

$$R^2 = \frac{\left[\sum_{i=1}^{n}(S_i - \overline{S})(O_i - \overline{O})\right]}{\sum_{i=1}^{n}(S_i - \overline{S})^2(O_i - \overline{O})^2} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{m}(S_i - \overline{S})^2} \quad (2)$$

$$nRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{m}(S_i - \overline{S})^2}}{\overline{O}} \quad (3)$$

$$D = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}\left(|S_i - \overline{O}| + |O_i - \overline{O}|\right)^2} \quad (4)$$

where S_i and O_i were the simulated and observed values; $\overline{S}$ and $\overline{O}$ were the mean of simulated and observed values, respectively; n was the sample number.

2.5. Data Analysis

In this experiment, the study area was mapped using ArcGIS10.8, and the measured data were analyzed and plotted using Origin 2021 and GraphPad Prism 8 software. The least significant difference (LSD) post-test at $p < 0.05$ was used to identify differences. Partial least squares path modeling (PLS-PM) was used to explore the effects and the contributions of tillage methods and straw returning on trends in SOC and crop yield under two climate scenarios, and the data used are the change slopes of each indicator over a hundred years.

We also calculated the SOCD [43,44], which is the storage capacity of SOC in the soil layer at a certain depth per unit area, with the formula shown in Equation (5):

$$SOCD = \sum_{i=1}^{k} SOCD_i = \sum_{i=1}^{k} C_i \times D_i \times H_i \times (1 - S_i)/100 \quad (5)$$

where SOCD is the soil organic carbon density (kg·m^{-2}), $SOCD_i$ is the organic carbon density of the i-th soil layer (kg·m^{-2}), C_i is the SOC content (g·kg^{-1}), D_i is the soil bulk weight (g·cm^{-3}), H_i is the soil layer thickness (cm), and S_i is the volume content of soil gravel > 2 mm (%).

3. Results

3.1. Agreement Between Observed and Simulated Values

In this experiment, for maize yield, the calibrated APSIM-maize model had an R^2 of 1.00, nRMSE of 3%, and D-index of 0.99; further validation of the model yielded an R^2 of 0.94, nRMSE of 6%, and D-index of 0.80, indicating that the measured and simulated values had a good fit (Table 1). After a comprehensive evaluation, the model simulation result is "excellent". As a result, the model is able to accurately simulate changes in crop yields under future climate change.

Table 1. Simulated yield and measured yield of maize based APSIM-maize model.

	Year	Simulated Yield (kg/ha)	Measured Yield (kg/ha)	R^2	D-Value	Nrmse (%)
Calibration	2009–2011	9761	10,022	1.00	0.99	3
Validation	2012–2013, 2015	10,633	10,352	0.94	0.80	6

3.2. Characteristics of Future Climate Change Under Different Climate Scenarios

Climate change is an important factor affecting maize production in Northeast China. Figure 2 shows precipitation and temperature changes under RCP4.5 and RCP8.5 scenarios. Using 1980–2010 as the base period, the annual mean temperature from 2011 to 2100 under RCP4.5 is 9.0 °C, which is 1.9 °C higher than the base period. The highest temperature is 3.1 °C above the base period. The average annual precipitation from 2011 to 2100 is 710.5 mm, an increase of 72.7 mm compared to the base period. The maximum rainfall is 160.8 mm above the base period, which occurs from 2091 to 2100.

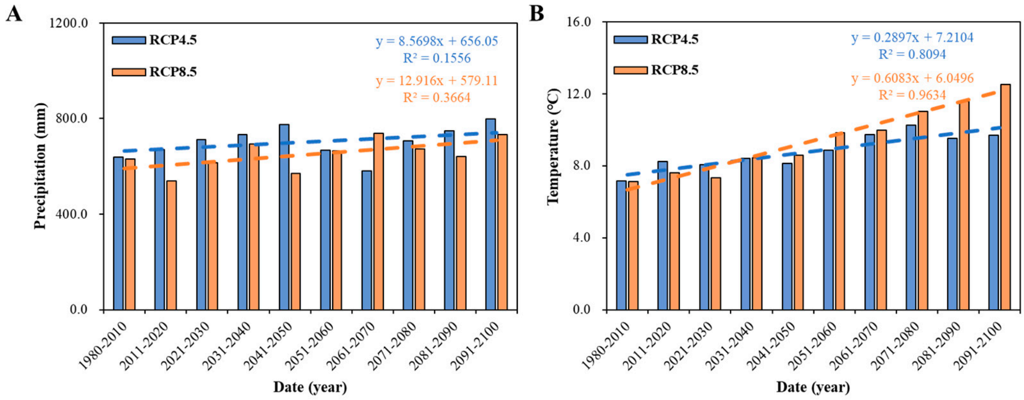

Figure 2. A comparison of the changes in mean annual precipitation (**A**) and mean annual temperature (**B**) under two typical concentration paths based on future climate models. The dashed line is the fitted linear trend line.

Under RCP8.5 climate scenarios, there was a greater increase in temperature and a smaller increase in rainfall, in which the average annual temperature was 9.7 °C in 2011–2100, which is 2.5 °C higher than the average annual temperature in the base period. The average rainfall is 652.2 mm in 2011–2100, which is 20.4 mm higher than the average annual rainfall in the base period. Under the RCP4.5 and RCP8.5 scenarios, precipitation increases by 8.6 mm $10a^{-1}$ and 12.9 mm $10a^{-1}$, respectively, while temperature rises by 0.29 °C $10a^{-1}$ and 0.61 °C $10a^{-1}$. The temperature increase trend is more pronounced and stable than the fluctuating precipitation trend in both scenarios.

3.3. Effects of Straw Returning Methods and Tillage Practices on Crop Yields Under Future Climate Scenarios

As shown in Figure 3, overall, crop yields are expected to slightly increase in the future under different tillage practices, with no-tillage (NT) showing the highest increase, followed by rotary tillage (RT) and plowing tillage (PT). Under the RCP4.5 scenario, the yield growth rate with straw return (SR) is higher than without straw return (SN). However, under the RCP8.5 scenario, the yield growth rate with SR is lower than with SN. This suggests that the effective utilization of straw might be lower under RCP8.5 compared to RCP4.5. The probable reason is that excessive warming under RCP8.5 causes more straw to convert into greenhouse gasses rather than soil nutrients. In general, however, there were no significant differences in the effects of straw-returning practices and tillage practices and their interactions with maize yield changes (Figure 4); the results could be due to excessive annual fluctuations or other unaccounted for climatic factors.

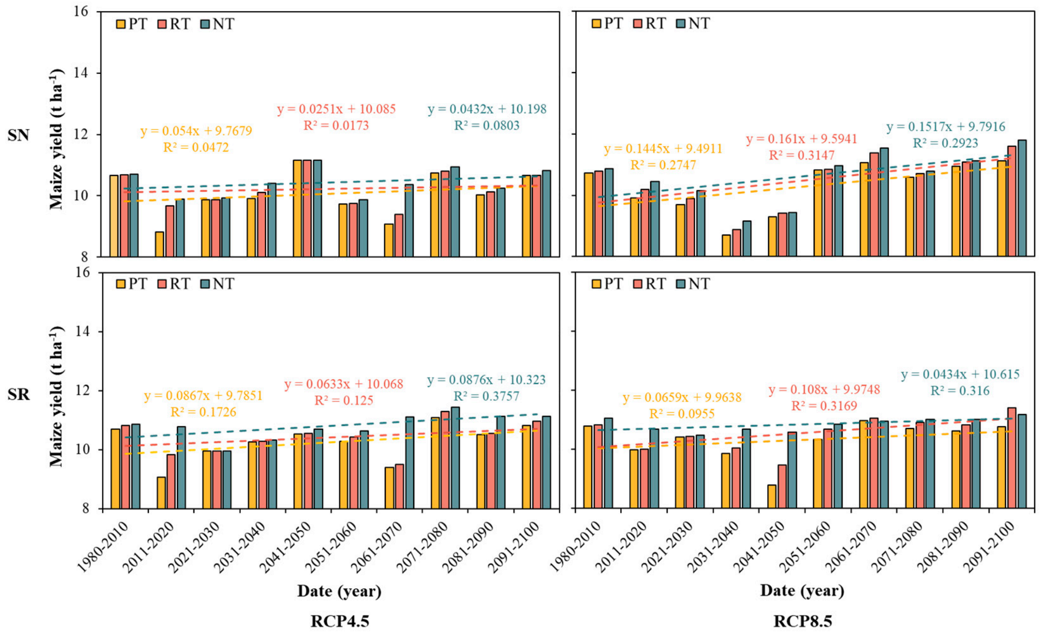

Figure 3. The variation in maize yield over time under different tillage practices and straw return methods under two climate scenarios (RCP4.5 and RCP8.5). The dashed line is the fitted linear trend line.

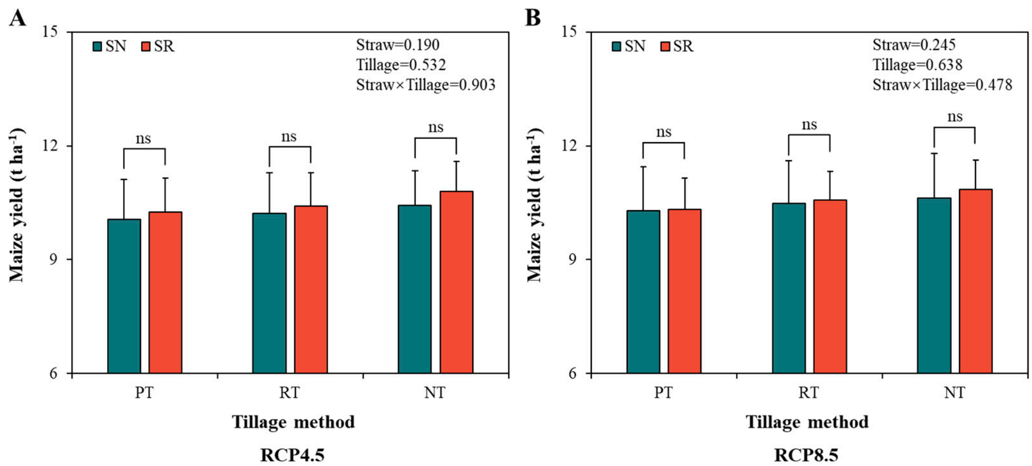

Figure 4. Effects of three tillage practices (PT, NT, RT) and two straw return practices (SN, SR) and their interactions on maize yield under RCP4.5 (**A**) and RCP8.5 (**B**) climate scenarios. ns: $p > 0.05$.

3.4. Effects of Straw-Returning Methods and Tillage Practices on SOC in Different Tillage Layers Under Future Climate Scenarios

Based on the results of Figure 5, SOC content in the 0–20 cm layer is highest under no-tillage (NT), both in SN and SR conditions and under both RCP4.5 and RCP8.5 scenarios. However, there is little difference between RT and PT when the straw is returned. Under both RCP4.5 and RCP8.5 scenarios, SOC decreases when straw is removed but increases when straw is returned (SR), indicating that straw return effectively mitigates the negative impact of climate scenarios on SOC. Especially, NT shows the highest SOC increase under SR condition and the lowest decrease under SN condition. This highlights the importance of no-tillage in combating the negative effects of climate change on soil SOC. The SOC content in the 20–40 cm soil layer decreases annually with the increase in time (Figure 6). The SOC content in the 20–40 cm soil layer shows similar decreasing trends across different climate change scenarios, tillage methods, and straw-returning methods, indicating that SOC changes in this layer are stable and unaffected by tillage or straw return. Under both climate scenarios and with the straw-returning method, NT and RT show slower SOC decline compared to PT.

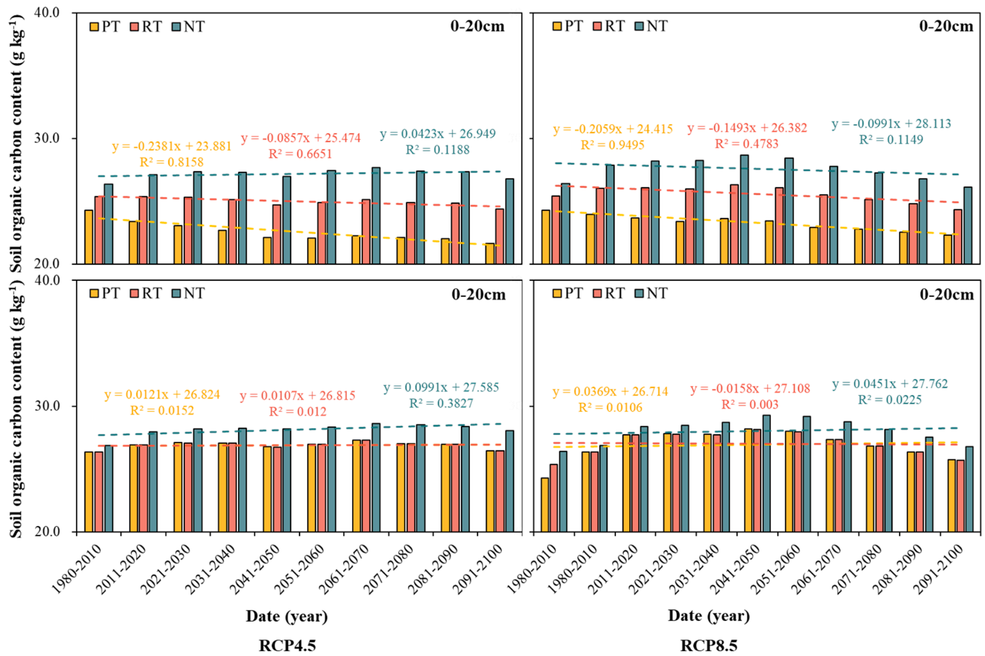

Figure 5. The variation in SOC content within the 0–20 cm soil tillage layer over time under different tillage practices and straw return methods under two climate scenarios (RCP4.5 and RCP8.5). The dashed line is the fitted linear trend line.

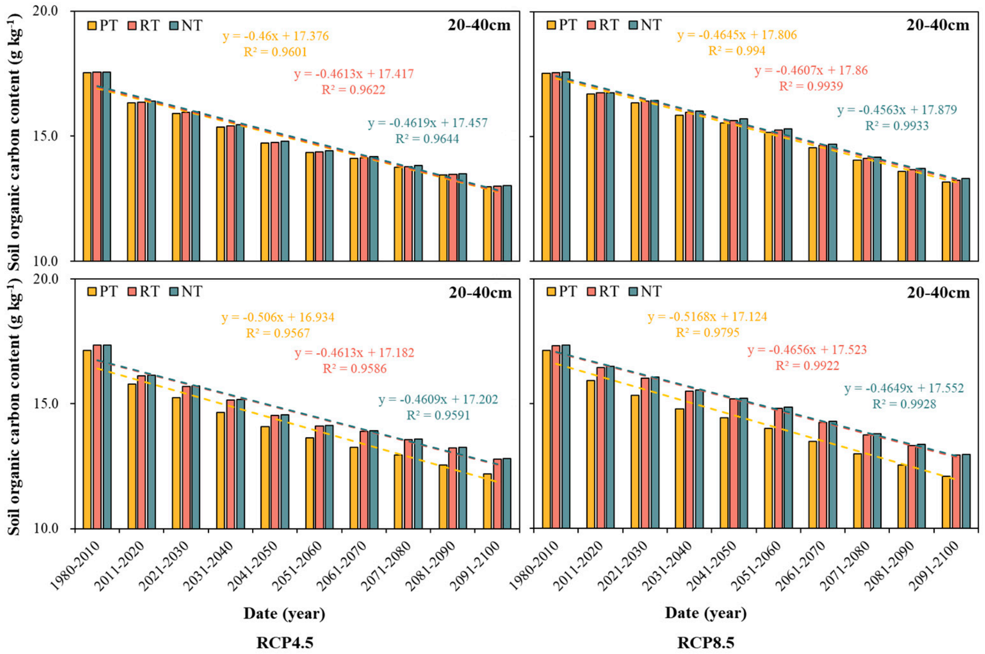

Figure 6. The variation in SOC content within the 20–40 cm soil tillage layer over time under different tillage practices and straw return methods under two climate scenarios (RCP4.5 and RCP8.5). The dashed line is the fitted linear trend line.

Overall, we found that different tillage methods, straw-returning methods, and their interaction all have significant effects on the SOC content of 0–20 cm under both RCP4.5 and RCP8.5 climate scenarios ($p < 0.001$, Figure 7A,B). Within the sub-tillage layer of 20–40 cm soils, overall, the effects of different tillage practices, straw-returning methods, and their interactions on SOC content are significantly different under the RCP4.5 climate scenario

($p < 0.05$ and $p < 0.01$) (Figure 7C) but are not significant under the RCP8.5 climate scenario (Figure 7D).

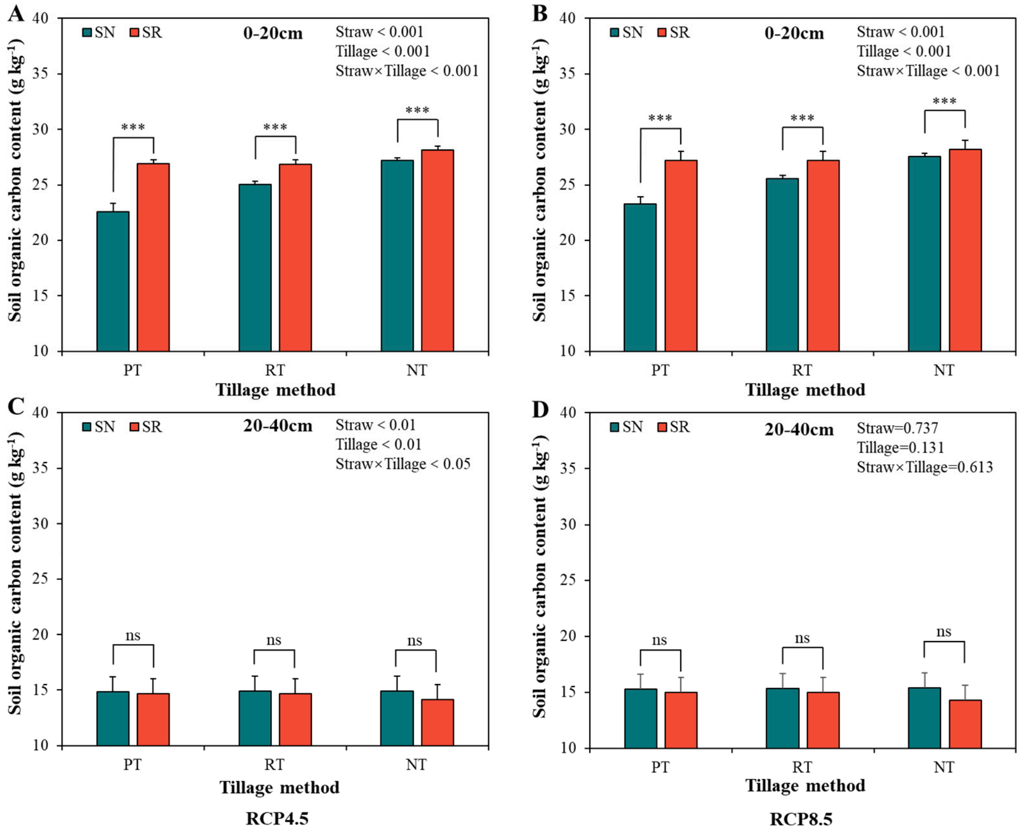

Figure 7. The effects of different tillage practices and different straw return methods on SOC in different tillage layers of the soil. Among them, (**A**,**C**) indicate the changes in SOC content of straw under RCP4.5 climate scenario with different return methods and different tillage methods, respectively, and (**B**,**D**) indicate the changes in SOC content of straw under RCP8.5 climate scenario with different return methods and different tillage methods, respectively. *** indicates the significant correlation at $p < 0.01$. ns: $p > 0.05$.

3.5. Changes in SOCD Under Different Straw Return Methods and Tillage Practices Under Future Climate Scenarios

Our simulation showed that SOCD decreases yearly with future warming under RCP4.5 and RCP8.5 (Figure 8). Straw return can mitigate this declining trend in SOC contents under climate change. By 2100 under RCP4.5, SOCD with no straw return (SN) decreases by 10.6%, 7.3%, and 7.2% for plowing tillage (PT), rotary tillage (RT), and no-tillage (NT), respectively, resulting in values of 59,971.27 kg ha^{-1}, 63,881.10 kg ha^{-1}, and 65,471.67 kg ha^{-1}. Under RCP8.5, SOCD decreases by 15.3%, 12.7%, and 10.5% for PT, RT, and NT, resulting in values of 56,877.06 kg ha^{-1}, 60,211.02 kg ha^{-1}, and 63,181.36 kg ha^{-1}. Under RCP8.5, SOCD decreases by 15.3%, 12.7%, and 10.5% for PT, RT, and NT, resulting in values of 56,877.06 kg ha^{-1}, 60,211.02 kg ha^{-1}, and 63,181.36 kg ha^{-1}.

Under straw return (SR), SOCD also decreased but remained higher under NT than PT and RT. By 2100 under RCP4.5, the SOCD values were 62,978.85 kg ha^{-1}, 62,911.36 kg ha^{-1}, and 64,498.86 kg ha^{-1} for PT, RT, and NT, respectively, with decreases of 10.2%, 10.3%, and 8.7% from the base period. Under RCP8.5, the SOCD values were 62,015.23 kg ha^{-1}, 61,933.28 kg ha^{-1}, and 64,286.83 kg ha^{-1} for PT, RT, and NT, respectively, with decreases of 11.6%, 11.7%, and 9.0% from the base period.

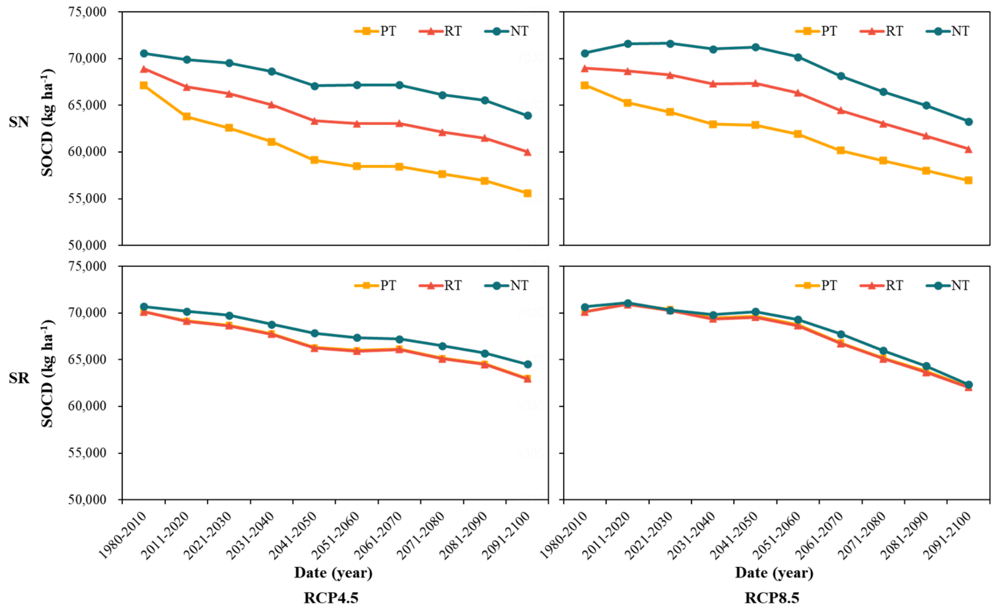

Figure 8. Changes in SOCD in 0–40 cm of farmland soils from 1980 to 2100 at Gongzhuling Experimental Station.

3.6. PLS-PM Analysis

Partial least squares path modeling (PLS-PM) was used to analyze the impact of different tillage practices and straw return under two climate scenarios on the future trend in maize yield (Figure 9). We found that under RCP4.5, the combined effects of tillage and straw returning contributed more to 57% yield changes compared to 54% under RCP8.5. The positive impact of tillage and straw return on 0–20 cm soil SOC and SOCD is more pronounced under RCP4.5 than RCP8.5. It implies that under more extreme climate change conditions, the positive effectiveness of conservation tillage may be somewhat reduced. Tillage practices and straw-returning methods mainly affect the 0–20 cm SOC contents. Furthermore, the coefficients of SOC change in 0–20 cm soil layer affecting SOCD change in 0–40 cm soil layer are 0.98 and 0.91, respectively, which are much higher than those of 0.31 and 0.56 in 20–40 cm soil layer. SOC and SOCD have significant effects on the final yield in the RCP4.5 scenario. However, the SOC and SOCD have no significant effects on the final yield in the RCP8.5 scenario. It also implies that under more extreme climate change conditions, more climate-smart practices will be needed to maintain the promising yield.

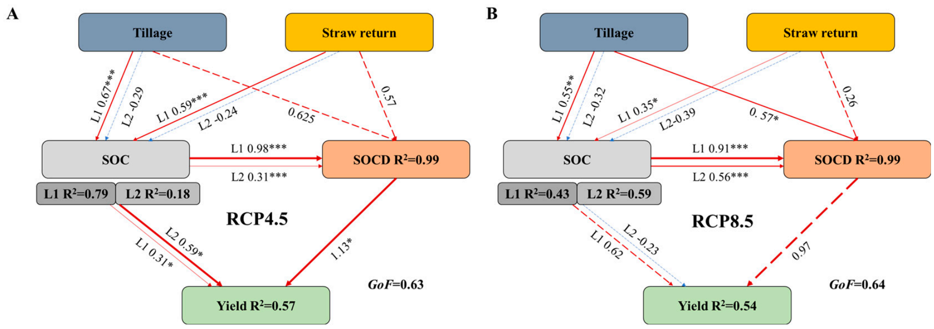

Figure 9. PLS-PM analysis of the combined effects of tillage and straw returning on yield under future climate scenarios. Single-headed arrows indicate the hypothesized direction of causation. The indicated values are the path coefficients. Red arrows indicate a positive effect, whereas blue arrows indicate a negative effect. The arrow width is proportional to the strength of the relationship. R^2 on the parameters indicates the percentage of the variance explained by other variables. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$. L1 is the first soil layer (0–20 cm), and the L2 is the second soil layer (20–40 cm). (**A**) Path analysis in RCP4.5 scenario; (**B**) Path analysis in RCP8.5 scenario.

4. Discussion

4.1. Maize Yield Under Climate Change

Previous studies have shown that the average temperature in northeast China will increase under future climate scenarios (RCP4.5 and RCP8.5) as the global average temperature increases due to carbon emissions increasing [45,46]. In this study, the effects of warming and reduced rainfall (Figure 2) were fatal to maize yield. It has been found that global warming leads to a shortening of the maize reproductive period and a significant shortening of the maize vegetative growth period, resulting in shorter and weaker maize plants and reduced maize dry matter accumulation; at the same time, higher temperatures make the maize plant respiration stronger, further enhancing the consumption of accumulated dry matter, which will have a seriously detrimental effect on maize yield [47–49]. However, tillage practices and straw returning did not have a significant effect on maize yield, possibly because these measures offset the negative effects of extreme drought, pests, and diseases caused by climate change.

As a result, the extreme decrease in maize yield under the RCP8.5 climate scenario (Figure 3) compared to RCP4.5 is attributed to reduced rainfall, continuous temperature increases, and extreme weather effects, such as severe droughts and freeze damage [50,51]. On the one hand, the increase in temperature and rainfall will affect the activity of some soil enzymes and enhance the metabolic activities of soil microorganisms [52,53]; on the other hand, climate change will cause local ecosystem dynamic changes in some areas under future climate scenarios. For example, climate warming will enhance soil respiration and accelerate SOC decomposition, in addition, global warming may also affect soil pH, which in turn will further affect soil microbial communities and soil enzyme activities, further affecting the rate of SOC decomposition [54–57].

4.2. Relations of Conservation Practices, Soil Quality, and the Maize Yield

It is worth noting that under the future climate scenarios, this experiment used the APSIM-maize model to study the effects of different straw return methods and different tillage practices on maize yield, and the results showed that the differences were not significant (Figure 4). Nevertheless, the effects of different tillage practices and straw return methods on SOC content within the 0–20 cm tillage layer varied significantly (Figure 8). Previous studies have shown that the use of no-till in monocropping systems can increase the surface SOC storage more effectively in areas with moderate temperature and low precipitation than in areas with high temperature, which is consistent with our findings [58].

Moreover, the return rate of straw returning to the field has also been proved to be significantly different under different climatic factors and soil texture [59]. Surprisingly, the SOC content showed a decreasing trend in the 20–40 cm soil tillage layer (Figure 7) and was lower under NT conditions than under PT and RT after straw return. The possible reason is that under NT measures, with the growth of time, the soil density increases under the effect of earth's gravity, soil pore space decreases, and the soil becomes compact, so the SOC within the sub-tillage layer is not better replenished [60], and the decomposition of SOC in the sub-tillage layer is faster in the context of global warming [61,62].

4.3. Limitation and Outlooks

There are still some limitations existing in this study. First of all, different ways of returning straw to the field have different effects on soil nutrients, but those were not compared in this study or captured by the model; in addition, the APSIM-maize model does not account for complex environmental and human factors present in field experiments, so its results approximate but do not fully replace field data when guiding actual management decisions. Therefore, agricultural producers should also choose reasonable farm management measures to ensure high maize yields according to local conditions; at the same time, we cannot ignore the decline in SOCD due to global temperature rise, which plays a crucial role in maintaining sustainable agricultural development, safeguarding soil fertility, and thus optimizing the northeast black land conservation policy [63].

This study draws on and summarizes innovations based on previous work, we applied the model simulation under the combinations of tillage practices, straw returning methods and different climate change scenarios, which may provide more insights on how to combine different practices as a "climate-smart management" package to ensure both food security and soil health. This study also systematically reveals the contribution of different tillage practices and straw-returning methods on SOC content and maize yield under climate change scenarios. Straw-returning and tillage practices explain around 50% of the yield changes. However, to address food security under future climate challenges, optimal combinations of practices tailored to local conditions, such as those in northwest China, are needed. Crop modeling serves as a powerful tool to gain these insights, aiding in decision-making and management.

5. Conclusions

The APSIM was well-validated for maize yield. The straw return can improve maize yield, increase SOC content in the cultivated layer, and positively improve SOCD in 0–40 cm. However, the simulation results of the APSIM showed that the three tillage practices, PT, RT and NT, as well as the two straw return practices, SN and SR, did not have significant differences in maize yield. In summary, under RCP4.5, tillage and straw return contribute to 57% of yield changes compared to 54% under RCP8.5. We simulated the effects of different tillage practices and straw return methods on maize yield, SOC, and SOCD under future climate models using the APSIM-maize model. This study underscores the importance of integrating effective tillage and straw management practices to sustain maize yields and SOC. Such combinations of climate-smart agricultural practices are crucial for mitigating the adverse effects of climate change on crop production and soil health. Moreover, it can analyze the influence of different tillage and straw management combinations on maize yield and soil carbon pool mechanism, explore the dynamic threshold under extreme climate, build a universal model optimization strategy, and explore new measures to improve soil carbon sequestration and crop adaptability, so as to strengthen the resilience and sustainable development efficiency of agriculture in response to climate change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy15010001/s1, Table S1. Parameters of APSIM model maize cultivars.

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